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# Doubly Resonant Ti:Sapphire Laser

Richard Scheps and Joseph F. Myers

**Abstract**—A CW Ti:sapphire laser is described that operates simultaneously at two frequencies. This mode of operation was obtained with an intracavity dispersive prism and two separate feedback paths. An alternative means of achieving dual frequency operation was demonstrated using a birefringent filter. Repetitive Q-switching produced an increase in the range of wavelengths over which dual frequency operation was obtained.

MULTIFREQUENCY operation of a tunable laser is typically an undesirable mode of operation. However, when there is independent wavelength and bandwidth control of each output wavelength the laser can be useful as a frequency multiplexing transmitter. This type of frequency agile laser is appropriate for such applications as differential absorption lidar (DIAL) and sum frequency generation. Early demonstrations of multifrequency devices concentrated on pulsed dye lasers [1]–[3], but recent advances in homogeneously broadened tunable solid-state lasers have provided an opportunity to demonstrate this type of operation in a more stable gain medium. The Ti:sapphire laser, with its broad tuning range and large stimulated emission cross section [4], is ideal for producing simultaneous output at more than one wavelength. In this letter we report the results obtained with an Ar-ion laser-pumped Ti:sapphire laser operating simultaneously at two wavelengths between 714 and 845 nm. This is the first time that the Ti:sapphire laser has been operated in this manner, and is also the first time simultaneous multifrequency operation has been demonstrated in a CW tunable laser.

The Ti:sapphire laser developed for this study is a modified version of a design reported by Schulz [5] and is shown in Fig. 1. Two concave mirrors with 10 cm radii of curvature (ROC) were used to concentrate the resonator mode in a 2 cm long Ti:sapphire rod with Brewster angle faces. These mirrors had broadband high reflector (HR) coatings over the range of 670–850 nm. The two flat HR mirrors were also broadband coated from 670–850 nm, while the output coupler was 96% R. The mode is collimated in the region of the resonator between each flat reflector and the nearest fold mirror, and a high-dispersion, low-insertion loss Brewster angle prism (Kigre M16 glass) was placed in the collimated region near one of the fold mirrors. The prism was oriented for minimum deviation, and independent tuning of each output wavelength was obtained by angular adjustment of the corresponding HR flat. Alternatively, the prism could be rotated to tune both wavelengths simultaneously. The meas-

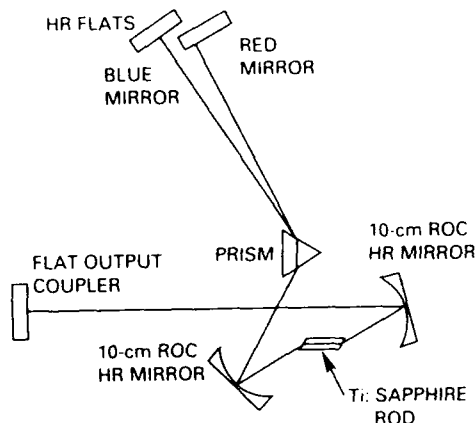


Fig. 1. Laser resonator showing the arrangement of optics for dual frequency operation. Mirror that produces shorter wavelengths is indicated as "blue" and longer wavelength mirror is labeled "red."

ured wavelength bandwidth was 1.2 nm, but this measurement was resolution limited.

Two separate feedback paths through the prism are provided by the pair of HR flats. The prism was typically oriented with respect to the flats so that the peak emission wavelength (780 nm) was beyond the interior edge of the "red" mirror. Alignment of the optics proceeded by adjusting the red mirror to produce a wavelength just to the red of the peak output. This mirror was then translated perpendicular to its normal to position the feedback axis as close to the interior edge of the coating as possible. The second HR flat (the "blue" mirror) was inserted behind and to the side of the red mirror such that the axis for this feedback path just cleared the edge of the red mirror substrate. It was adjusted to produce wavelengths to the blue of the peak. The resulting dual frequency output is emitted from the resonator in a single collinear beam. To demonstrate collinearity the output was expanded and the spatial superposition of the two wavelengths was verified by blocking one of the HR flats and detecting the position of the other with a digitizing CCD detector. A more sensitive measure of collinearity was obtained by translating the pump beam across the Ti:sapphire crystal and observing the simultaneous, correlated intensity variation for each wavelength. This verified that both feedback paths utilized a common active volume in the rod. The argon-ion laser pump output power level of 4.5 W was maintained for all measurements. The pump laser output polarization was rotated and focused onto the Ti:sapphire crystal with a 25 cm lens. The wavelength was monitored using a 0.3 m spectrometer in conjunction with an optical multichannel analyzer (OMA). A coarse (100 lines/mm) grating was used in first order, providing a range of approximately 400 nm for the 512 element OMA. This allowed simultaneous display of both wavelengths. A sample trace of

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dual wavelength operation recorded by the OMA is shown in Fig. 2.

The range of frequencies over which simultaneous multi-frequency operation can occur in a homogeneously broadened laser is determined primarily by gain competition. This can be understood by noting that in the case of a tunable laser with a single feedback path containing no frequency selective or bandwidth narrowing intracavity elements, the output consists of a band of frequencies centered near the peak of the gain curve. The spectral output of the untuned laser is determined by gain competition among resonant longitudinal modes. Injecting a resonant signal at a second wavelength which is within the tuning range of the laser will not result in partial locking (or equivalently, dual frequency operation) if the net saturated gain at the second wavelength is below threshold [6]. In fact, since the second wavelength is resonant in the free running laser, it would be emitted in the untuned device in any event were it not for gain saturation at the peak of the gain curve. With regard to the dispersed, doubly resonant device in Fig. 1, when one feedback path provides operation near the peak of the gain curve the gain clamps near threshold and frequencies for which the net gain is substantially lower will not oscillate. Single wavelength operation will therefore be produced even though there is feedback for a second wavelength. This simple interpretation of dual frequency dynamics in a CW tunable laser provides a qualitative framework to explain much of the performance data obtained for the doubly resonant laser.

By removing one of the HR flats the laser operates as a single wavelength device. The maximum power obtained with the prism in the cavity was 460 mW at 780 nm, but the peak was broad and power near the maximum was maintained over the range of 770–790 nm. The wavelength dependence of the power is shown in Fig. 3. As a dual wavelength laser the total power was a more complicated function of wavelength owing to gain competition between the two operating frequencies. The total power obtained ranged from 80 mW for data pairs where both wavelengths were in the wings of the tuning curve to 350 mW for wavelength pairs near the peak. In Fig. 4 we have shown the wavelengths pairs for which simultaneous dual frequency operation was achieved. To the extent that the mirror coatings do not extend to the edges of the HR flats there was some "dead space" in the wavelength tuning of the laser. This was approximately 10 nm. There are two mechanisms that limit the tuning range for dual frequency operation. The first is the gain competition discussed earlier, which prevents operation at two frequencies when the net gain of one is substantially lower than that of the other. As a consequence, the highest concentration of data points shown in Fig. 4 is near the locus of wavelength pairs for which the measured single wavelength output power is equal (solid line). There are only a few points near the peak of the gain curve for the same reason. The other limiting mechanism is a result of geometric constraints associated with the two feedback paths. When tuning with only the feedback mirrors (prism is fixed) the tuning range of the red mirror cannot be extended to the blue past the wavelength where the dispersed frequencies lie

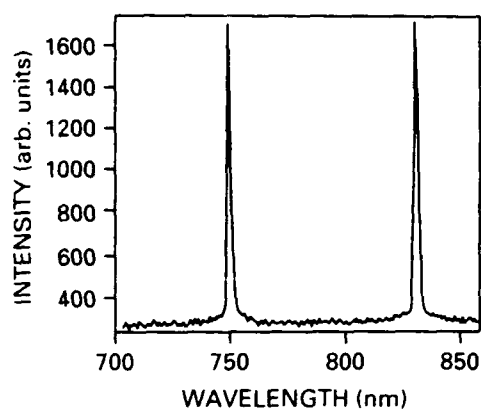


Fig. 2. Sample spectral output for simultaneous dual frequency operation. Wavelengths are 750 and 830 nm. The total output power obtained in this case was 330 mW.

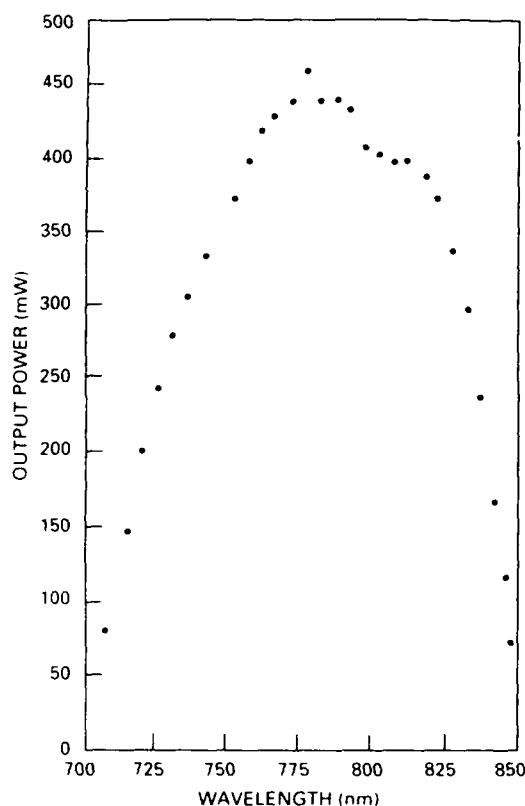


Fig. 3. Single wavelength tuning range of the Ti:sapphire laser using intracavity prism and an ion laser pump power of 4.5 W.

beyond the interior edge of the coating ("walkoff"). Similarly, the red wavelength limit for the blue mirror is determined by the mirror angle at which the edge of the red mirror blocks the blue mirror feedback ("vignetting"). Translation of the HR flats transverse to the mode axis is required to produce the range of dual wavelength operation shown in Fig. 4, but in several instances vignetting or walkoff bounded the operating range. While changes in the resonator configuration will extend the tuning range when geometric constraints define the limit, the dual wavelength operating range shown in Fig. 4 is determined primarily by gain competition. This range was extended by inserting an

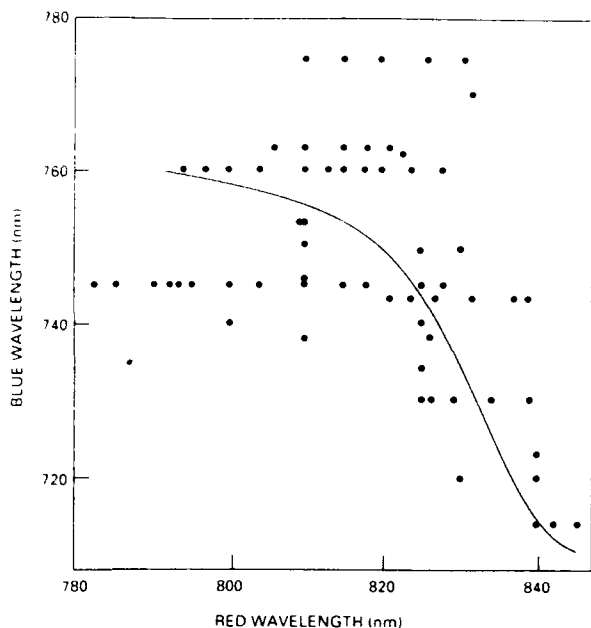


Fig. 4. Wavelength pairs produced simultaneously with the Ti:sapphire laser. Minimum blue wavelength and maximum red wavelength for axes were selected to match the single wavelength operating range. Solid line is locus of wavelength pairs for which the measured single-wavelength output power (Fig. 3) is approximately equal.

intracavity mechanical  $Q$ -switch. Although the switching rate was low (3 KHz) relative to the upper laser level lifetime, the increase in gain was enough to extend the range by approximately 10 nm. By  $Q$ -switching it was also possible to observe the temporal evolution of emission at each of the two wavelengths. It was found that temporal superposition of the two wavelength pulses occurred only when there was spatial superposition of each feedback path in the active volume.

Over 670 mW was obtained at 780 nm by replacing the prism with a three-plate birefringent filter (BRF) and using a single HR feedback mirror. The BRF was designed with a small free spectral range in order to provide for two trans-

mission peaks over the wavelength range shown in Fig. 3. Dual frequency operation was obtained with output at 720 and 830 nm and could be tuned over several nanometers. While this method of obtaining two frequencies gives higher power and ensures that the two wavelengths will be emitted collinearly, it has the obvious limitation that after fabrication the separation between the two wavelengths cannot be changed. As a consequence the range for dual wavelength operation is limited.

In summary, we have measured the performance characteristics of a CW, dual frequency Ti:sapphire laser. The maximum output power was 350 mW, and dual wavelength operation was obtained over a relatively large wavelength range. The operating range was increased further by repetitive  $Q$ -switching and is expected to be considerably expanded with pulsed pumping. Using a BRF for dual frequency operation, 506 mW of total power was obtained but with a greatly restricted wavelength range. It is worth noting that although no attempts were made to narrow the bandwidth of either wavelength, etalons or other narrowing elements can be inserted in the resonator to produce extremely narrow linewidths. Operation with a reduced bandwidth should be accompanied by higher efficiency than is generally obtained with a traditional single-frequency standing wave laser since spatial hole burning will be reduced owing to the simultaneous production of two wavelengths.

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